Journal of Nondestructive Evaluation, Vol. 25, No. 1, March 2006 (© 2006)
DOI: 10.1007/s10921-006-0003-8

Eddy Current Assessment of Near-Surface Residual Stress in Shot-Peened Inhomogeneous Nickel-Base Superalloys

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Received 3/1/05; revised 5/23/05; Published online: 5/16/06

Recently, it has been shown that shot-peened nickel-base superalloys exhibit an approximately 1% increase in apparent eddy current conductivity at high inspection frequencies, which can be exploited for nondestructive subsurface residual stress assessment. Unfortunately, microstructural inhomogeneity in certain as-forged and precipitation hardened nickel-base superalloys, like Waspaloy, can lead to significantly larger electrical conductivity variations of as much as 4–6%. This intrinsic conductivity variation adversely affects the accuracy of residual stress evaluation in shot-peened and subsequently thermal-relaxed specimens, but does not completely prevent it. Experimental results are presented to demonstrate that the conductivity variation resulting from volumetric inhomogeneities in as-forged engine alloys do not display significant frequency dependence. This characteristic independence of frequency can be exploited to distinguish these inhomogeneities from near-surface residual stress and cold work effects caused by surface treatment, which, in contrast, are strongly frequency-dependent.

KEY WORDS: Eddy current; shot peening; inhomogeneity; residual stress.

1. INTRODUCTION

Shot peening is known to improve the resistance to fatigue and foreign object damage in metallic components due to its damage arresting qualities. This surface enhancement process, which introduces beneficial residual stresses and hardens the surface, is widely used in a number of industrial applications, including gas-turbine engines. Modern aircraft turbine engine components are designed using a damage-tolerance philosophy that allows the prediction of a given component's useful service life based on fracture mechanics and structural analysis. However, the fatigue life improvement gained via surface enhancement is not explicitly accounted for in current engine component life management processes because of the uncertainty about the long-term stability of the protective near-surface residual stress at high operational temperatures. Therefore, there is a significant potential for increasing the predicted damage tolerance capabilities of components if beneficial residual stress considerations are incorporated into the life prediction methodology. Nondestructive inspection of components for near-surface flaws is a critical part of life assessment for many US Air Force engine applications. A major barrier to introducing subsurface residual stress information into the life calculation process is the necessity to make accurate and reliable nondestructive measurements on shot-peened components.

Eddy current inspection is a promising candidate for use in characterizing the residual stresses resulting from shot peening.[1–10] Unfortunately, it is well known that, beside the sought residual stress,

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **23 MAY 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Eddy Current Assessment of Near-Surface Residual Stress in Shot-Peened Inhomogeneous Nickel-Base Superalloys**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AFRL,Metals, Ceramics, and NDE Division,Wright-Patterson AFB,OH,45433-7817**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the measured eddy current conductivity is affected by a number of factors, such as chemical composition, microstructure, hardness, surface roughness, temperature, etc. Recently, it has been found that, in contrast with most other materials, shot-peened nickel-base superalloys exhibit an apparent increase in eddy current conductivity at increasing inspection frequencies, which can be exploited for nondestructive residual stress assessment of subsurface residual stresses.(10) This observation by itself seems to indicate that in these materials the measured conductivity change is dominated by residual stress effects, since surface roughness, increased dislocation density, and increased permeability are all known to decrease rather than increase the apparent eddy current conductivity. It has been also shown that in intact shot-peened specimens, the excess apparent eddy current conductivity (AECC) is roughly proportional to the peening intensity(10) and the frequency dependence of the AECC is consistent with the penetration depth of the compressive residual stress distribution.(11) Furthermore, on partially relaxed shot-peened Waspaloy specimens the measured AECC difference has been found to change more or less proportionally to the remaining subsurface residual stress. Finally, on fully relaxed specimens the AECC completely vanished, which indicates that it is fairly selective to the residual stress contribution since the cold work effect did not entirely disappear.(10) The observed close correlation between the AECC and X-ray diffraction (XRD) residual stress data indicates that the eddy current approach has the potential to be exploited for nondestructive characterization of subsurface residual stresses in surface-treated nickel-base superalloys. Further research has revealed that the depth profile of the intrinsic electrical conductivity of the specimen can be predicted from the measured frequency-dependent AECC by a simple inversion technique.(11) Then, the conductivity profiles obtained from such inversion can be used directly to assess the existing residual stress profile based on the empirically determined electro-elastic coefficient of the material.(12)

The microstructure of nickel-base superalloys consists of several important microstructural features, namely a Ni-rich matrix, reinforcing Ni3(Al,Ti) gamma prime precipitates, and carbide phases at the grain boundaries. The size distribution of the gamma prime precipitates is determined by the precipitation hardening treatment used, while the shape is most often controlled by composition. The matrix grain size and the carbide distribution are affected by the forging temperature and the alloy composition. It is speculated that when large forgings of these materials are fabricated, the matrix grain size and the carbide distribution are inhomogeneous. These inhomogeneities, in turn, could affect the gamma prime reinforcing microstructure and thus lead to eddy current conductivity anomalies. It should be mentioned that the nickel-base superalloy specimens used in Ref. 10 were fully annealed before shot peening to eliminate essentially all variations in material properties. From a practical point of view, there is a need for a detailed study of the complex relationship between the measured nondestructive signature, material microstructure, and residual stress and cold work effects due to surface treatment. In particular, the relationship between the nondestructive signature and residual stress relief at service temperatures is of great significance. It is important to understand the effect of microstructural anomalies leading to measurement fluctuations and their effect on residual stress measurements, since it is critical for the interpretation of the eddy current residual stress results obtained on surface-treated and subsequently thermally relaxed nickel-base superalloys.

In this paper, we study the electrical conductivity distribution in three typical polycrystalline nickel-base superalloys used in turbine engine applications, namely Waspaloy, IN718, and IN100, using absolute eddy current conductivity measurements and high-resolution eddy current imaging. We will demonstrate that the conductivity variations resulting from microstructural inhomogeneities in as-forged engine alloys (Waspaloy and IN718) are mostly due to volumetric effects, therefore they do not exhibit significant frequency dependence in the 100 kHz to 10 MHz frequency range used for near-surface residual stress assessment in shot-peened components. This independence of the apparent eddy current conductivity from frequency allows us to distinguish these inhomogeneities from near-surface residual stress and cold work effects caused by surface treatment, which both exhibit strongly frequency-dependent AECC difference between peened and unpeened states.

2. INHOMOGENEITY AND EDDY CURRENT MEASUREMENTS

In order to achieve a better understanding of the nature of the electrical inhomogeneity that occurs in nickel-base superalloys, we first compared

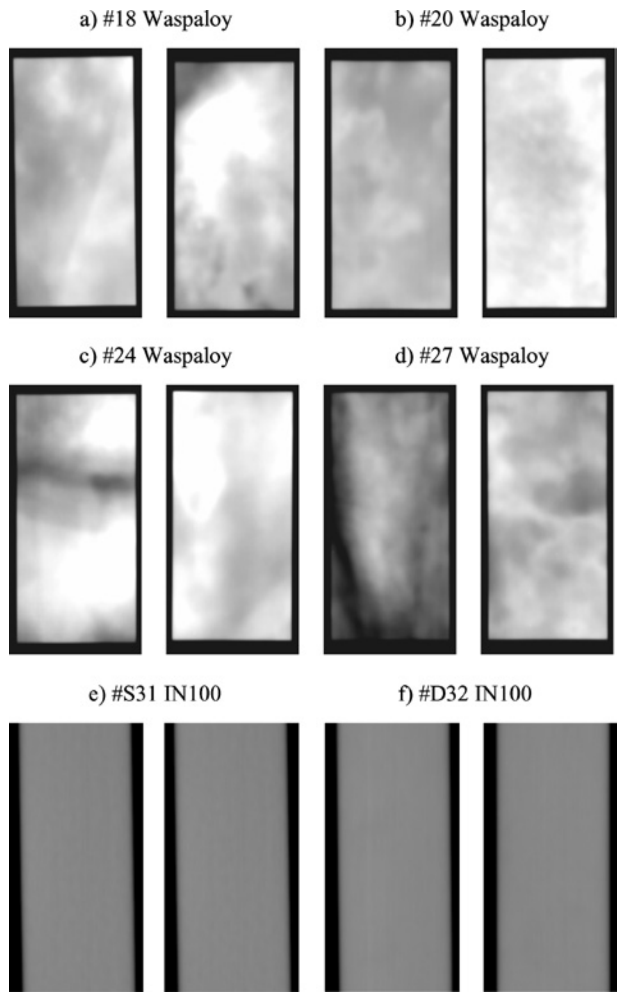

Fig. 1. Examples of the eddy current conductivity distribution in four inhomogeneous Waspaloy specimens (as-forged, unpeened, 6 MHz, 53 mm × 107 mm, conductivity range is 1.38–1.47% IACS or ±3.2% in relative terms) and two homogeneous IN100 specimens (power metallurgic, unpeened, 6 MHz, 28 mm × 56 mm, conductivity range is 1.337–1.341% IACS or ±0.13% in relative terms).

the-electrical conductivity distribution in as-forged (Waspaloy) and power metallurgic (IN100) nickel-base superalloy specimens using high-resolution eddy current imaging. The eddy current images were taken by a ≈2-mm-diameter pencil probe at 6 MHz with a Staveley Nortec 2000S Eddyscope as the specimens were scanned using an *x*–*y* table driven by a VELMEX 86 mm motor controller. Prior to scanning, the surface of the specimen was carefully aligned with the scanning plane of the *x*–*y* table, the probe was adjusted to a constant nominal lift-off distance of $\ell = 0.1$ mm, and the phase angle of the Nortec 2000S was appropriately set to align the inevitable remaining lift-off variations to the horizontal direction. The vertical analog output of the eddy current instrument, corresponding to the apparent eddy current conductivity, was fed to a computer and stored as an image.

Eddy current conductivity maps of several Waspaloy specimens from the same batch indicated that inhomogeneities, as large as 20–30 mm, can exist in the as-forged and precipitation hardened alloy. Figure 1 shows examples of typical eddy current conductivity images from both sides of four inhomogeneous Waspaloy specimens (a through d) and two homogeneous IN100 specimens (e and f) taken at 6 MHz. The Waspaloy specimens were 53 mm × 107 mm and exhibited a wide conductivity range from ≈1.38%IACS to ≈1.47 %IACS, or ±3.2% in relative terms. In contrast, the 28 mm × 56 mm IN100 specimens exhibited a very narrow conductivity range from 1.337–1.341%IACS or ±0.13% in relative terms. It should be mentioned that similar images of IN718 specimens revealed a similarly low level of inhomogeneity (for brevity, the scanned images of IN718 are not presented in this paper). It is postulated that the observed electrical inhomogeneity difference between Waspaloy, IN718, and IN100 is caused by their different alloy composition and thermo-mechanical processing and it is somehow related to the microstructure of these materials.

Since the main applications for surface-treated nickel-base superalloys are in high-temperature turbine engine components, for the purposes of developing a quantitative eddy current method for residual stress measurement in these alloys after thermal relaxation, it is essential to understand the electrical conductivity variation caused by thermal exposure. As a starting point, eight intact specimens of each Waspaloy, IN718, and IN100 were annealed by repeated application of 24-h heat treatments in Argon protective environment between 300 °C and 800 °C in 50 °C-steps, followed by absolute AECC measurements at 500 kHz with a 9-mm-diameter pancake probe specially designed for precision conductivity measurements and a Staveley Nortec 2000S eddy current instrument.

The standard four-point linear interpolation procedure used to determine the apparent eddy current conductivity is illustrated in Figure 2, which shows a schematic representation of the electrical impedance of the probe coil in the complex plane before (a) and after (b) zoom-in and rotation. Four reference points are measured on two appropriate calibration blocks with ($\ell = s$) and without ($\ell = 0$) a polymer foil of thickness s between the probe coil and the specimens. For the small conductivity variations considered in this study, sufficiently accurate results can be achieved by choosing two calibration blocks that closely bracket the conductivity range of interest. Then, the unknown apparent conductivity σ_a and lift-off ℓ_a, if necessary, can be calculated from the complex coil impedance $Z(\sigma_a, \ell_a)$ produced by the actual specimen using this simple linear interpolation. Because of the high precision requirements of these measurements, efficient rejection of inevitable

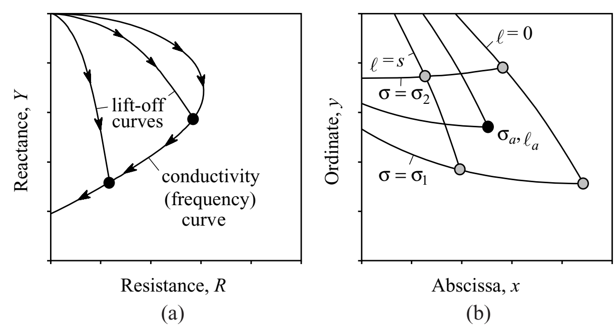

Fig. 2. A schematic representation of the eddy current probe coil impedance in the complex plane before (a) and after (b) zoom-in and phase-rotation demonstrating the four-point linear interpolation procedure for assessment of the apparent eddy current conductivity.

lift-off variations is of the utmost importance. It was also necessary to periodically repeat the calibration procedure during manual scanning in order to reduce the adverse effects of thermal drift caused by the weak, but still perceivable instability of the probe and the instrument. For the above absolute measurements, the experimental system was calibrated using two standard reference blocks of $\sigma_1 = 1.34\%$ IACS and $\sigma_2 = 1.48\%$ IACS and an $s = 0.025$ mm thick polymer foil for controlling lift-off.

Figure 3 shows the evolution of electrical conductivity and corresponding inhomogeneity in these three nickel-base superalloys during gradual thermal exposure. Initially, the average conductivity values of all three nickel—base superalloys tend to decrease after thermal exposure at temperatures around 350–450 °C. The biggest conductivity drop occurs around 500–550 °C, then the conductivity values continue to rise to their respective maxima at around 750 °C, where a notable increase in conductivity occurs in comparison with the respective initial values in the intact materials. In addition to the above described overall trend of changing average electrical conductivity, Figure 3 also illustrates the changing level of inhomogeneity during thermal exposure, especially in Waspaloy and, to a much lesser degree, in IN718. By far the strongest inhomogeneity among these materials is observed in Waspaloy. Interestingly, the inhomogeneity initially decreases up to about 450 °C, then increases and peaks at around 550 °C. Above this temperature the inhomogeneity gradually decreases and at around 650 ° it completely vanishes. The inhomogeneity observed in IN718 and IN100 remains very small over the whole temperature range, except for a slight increase in IN718 at around 600 °C, which appears to be related to the

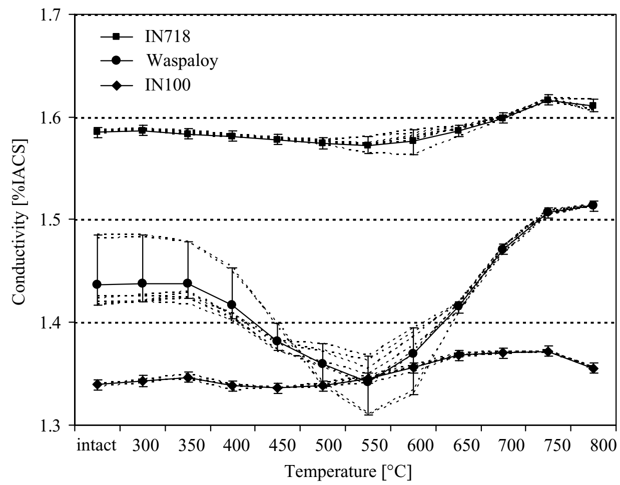

Fig. 3. The evolution of electrical conductivity and corresponding inhomogeneity in three nickel-base superalloys (8 of each material) during gradual thermal exposure.

similar but much stronger increase in inhomogeneity exhibited by Waspaloy.

The above results suggest that further research is necessary to study the role of spurious background variations caused by microstructural anomalies in nickel-base superalloys to facilitate reliable eddy current residual stress assessment of subsurface residual stresses. We chose Waspaloy as a "worst-case" example of nickel-base superalloys to further study the relationship between conductivity variations and microstructural features. In order to determine whether the characteristic features observed in the above eight Waspaloy specimens during thermal exposure are reproducible or not, we prepared a larger series of 32 as-forged specimens and repeated the same thermal exposure experiments up to a 150 °C higher temperature than before. These specimens were annealed by repeated application of 24-h heat treatments in Argon protective environment between 300 °C and 950 °C in 50 °C-steps, followed by absolute AECC measurements. Figure 4 shows the evolution of electrical conductivity and corresponding inhomogeneity in these Waspaloy specimens during gradual thermal exposure. It should be noted that the conductivity drop after 850 °C is probably due to excessive corrosion produced during the exposure process. Otherwise, these specimens exhibited very similar behavior to the previously observed one. Interestingly, both Figure 3 and Figure 4 suggest that spots of the highest conductivity in the initial state tend to exhibit the lowest conductivity at around 550 °C, an observation that might help to pin-point the microstructural feature mainly responsible for the conductivity inhomogeneity in the future.

3. RESIDUAL STRESS AND THERMAL RELAXATION

The change of electrical conductivity due to the presence of near-surface residual stresses is always

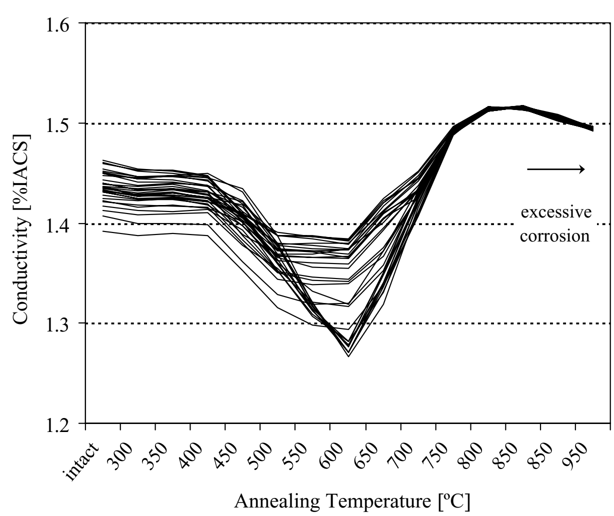

Fig. 4. The evolution of electrical conductivity and corresponding inhomogeneity in 32 as-forged commercial Waspaloy specimens during gradual thermal exposure.

very small, typically less than 1%.[10,11] Therefore, the roughly 3–4% electrical conductivity variation exhibited by inhomogeneous Waspaloy specimens raises a crucial question. Can eddy current techniques detect, let alone quantitatively characterize, near-surface conductivity variations caused by surface treatment in the presence of stronger conductivity variations caused by microstructural inhomogeneity in certain nickel-base superalloys?

In order to answer this question, we applied eddy current imaging to study the electrical conductivity distribution in different nickel-base superalloy specimens which were only shot-peened over half of their surface. Figure 5 shows typical examples of conductivity images of shot-peened IN100, IN718, and Waspaloy specimens of different peening intensity taken at 6 MHz (53 mm × 107 mm). In all cases, the bottom halves of the specimens were peened therefore appear to be brighter, i.e., of slightly higher conductivity, than the untreated top halves. In the case of IN100, the background inhomogeneity of the conductivity distribution is negligible with respect to the excess conductivity caused by peening. In comparison, the more significant inhomogeneity of the forged IN718 specimens is comparable to the modest conductivity increase caused by peening. Finally, in the case of the highly inhomogeneous Waspaloy specimens, the inhomogeneity (3–4%) is significantly stronger than the effect of shot peening (0.5–1%), therefore could seriously distort eddy current assessment of near-surface residual stresses.

Figure 6 shows the conductivity images of a 51 mm × 102 mm shot-peened inhomogeneous Waspaloy specimen of Almen 8A peening intensity at nine different inspection frequencies over a wide frequency range from 250 kHz to 10 MHz. Again, the upper half of the specimen is the untreated surface and the lower half is the peened surface. Although at the highest inspection frequencies the peened lower half appears to be consistently brighter, i.e., of higher

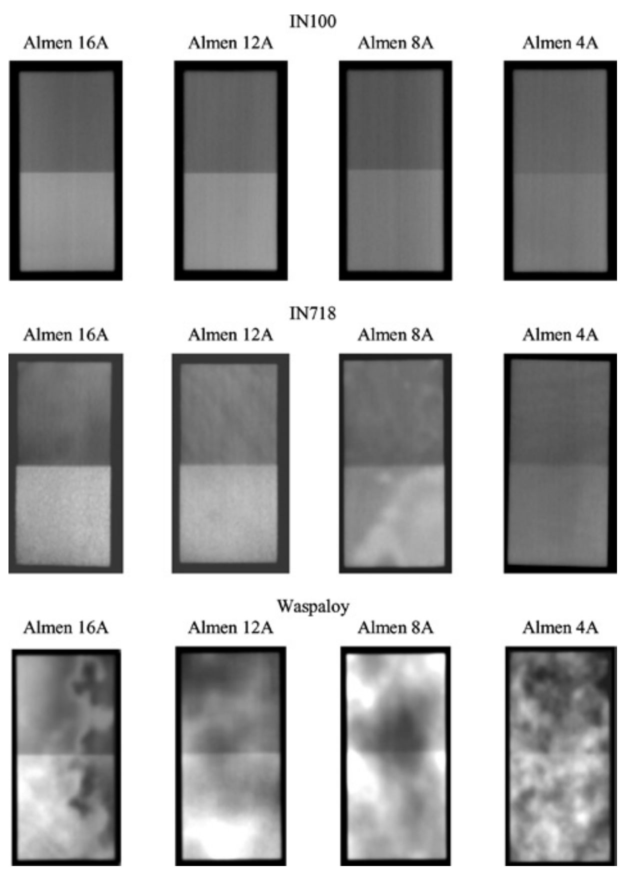

Fig. 5. Conductivity images of shot-peened IN100, IN718, and Waspaloy specimens of different peening intensity taken at 6 MHz (53 mm × 107 mm).

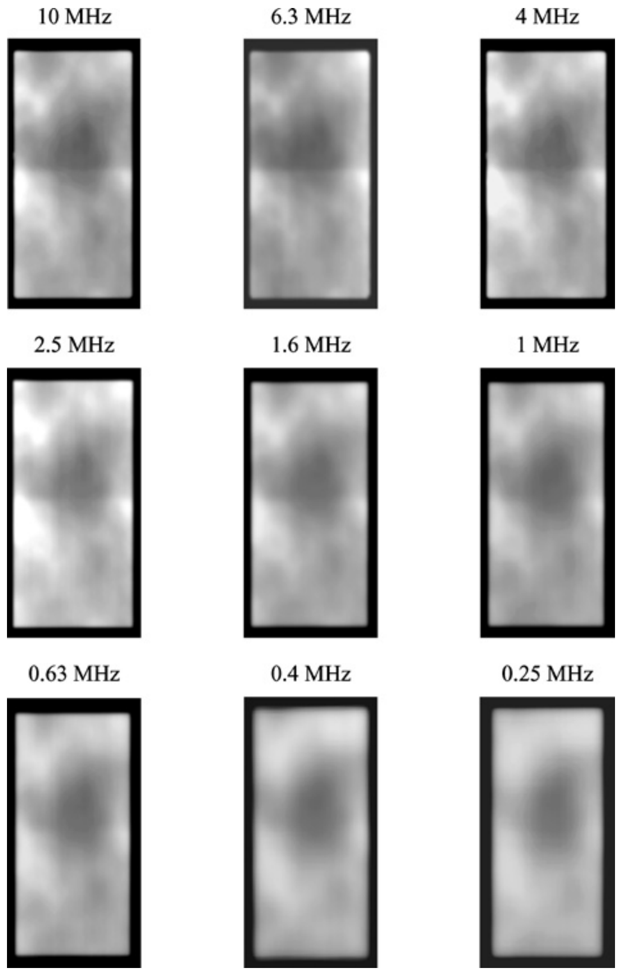

Fig. 6. Conductivity images of a shot-peened inhomogeneous Waspaloy specimen at nine different inspection frequencies (Almen 8A, 53 mm × 107 mm).

conductivity, than the untreated upper half, the conductivity difference resulting from the weak residual stress effect between the peened and unpeened areas is all but hidden by the stronger intrinsic inhomogeneity of the specimen.

Eddy current images of inhomogeneous Waspaloy specimens indicate that low- and high-conductivity domains as large as 25 mm can exist in the as-forged and precipitation hardened alloy. Since the depth of the compressed near-surface layer in moderately shot-peened nickel-base superalloys reaches only 100–200 μm, the corresponding weaker, but frequency-dependent part of the AECC variation can be relatively easily separated from the stronger, but frequency independent contribution of the bulk inhomogeneity. It is obvious from Figure 6 that the background variation of the AECC is essentially frequency independent due to the large volumetric size of the inhomogeneous domains. In order to verify this conclusion, we measured the AECC on four spots of an unpeened inhomogeneous Waspaloy specimen over a wide frequency range from 100 kHz to 10 MHz. The results of this experiment are shown in Figure 7. As the frequency decreases, the eddy current penetrates deeper into the material and also spreads a little wider in the radial direction. Although there is some change in the AECC with frequency at most locations, on the average this frequency dependence essentially cancels out for many points.

The lack of strong frequency dependence in the inhomogeneity induced AECC variation suggests that the conductivity does not vary sharply with

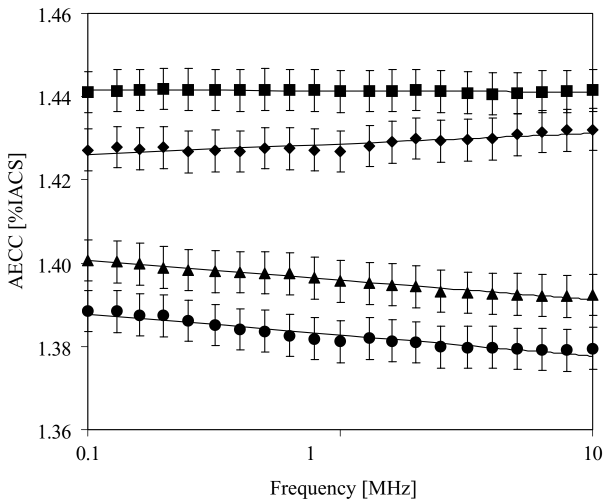

Fig. 7. AECC spectra in an as-forged unpeened Waspaloy specimen at four different locations.

depth, which can be exploited to separate the primary residual stress effect from the spurious material inhomogeneity using point-by-point absolute AECC measurements over a wide frequency range, followed by a comparison of the near-surface properties measured at high frequencies to those at larger depth measured at low-frequencies. This is a significantly more time consuming measurement than the simple scanning technique developed in Ref. 10 to compare the average AECC of large peened and unpeened areas to calculate the peening-induced average AECC increase in homogeneous Waspaloy specimens after full annealing. Comparing the AECC at high and low inspection frequencies is equivalent to comparing the electrical conductivity of every spot on the shot-peened surface to a reference point slightly below the same spot, therefore it represents the best self-referencing measurement one can make under these difficult conditions.

In order to verify whether this absolute measurement technique is capable of sensing the weak AECC change due to residual stress effects in inhomogeneous specimens, a series of experiments were conducted in intact shot-peened Waspaloy samples of different peening intensity. These measurements were made by a Staveley Nortec 2000S eddy current instrument with three different probes to assure optimal sensitivity over a wide frequency range from 100 kHz to 10 MHz. The instrument was calibrated at each inspection frequency using two calibrated reference blocks of $\sigma_1 = 1.34\%$ IACS and $\sigma_2 = 1.43\%$ IACS using an $s = 0.025$ mm thick polymer foil for controlling the lift-off distance. In order to reduce the adverse effects of statistical variations in the local conductivity over the 51 mm × 51 mm peened and unpeened areas, we repeated all measurements at 18 different locations on the surface of the specimen (9 points each on the peened and unpeened sides). Then, we averaged the data for each frequency, to reduce the incoherent scatter in the data caused by thermal drift, electrical noise, imperfect lift-off rejection, etc.

During measurements, a template was used to position the eddy current probe so that exactly the same points would be inspected at different frequencies. A quick comparison between the diameter (≈2–3 mm) of the eddy current probe coils used in our study and the typical size of inhomogeneous regions (≈20–30 mm) observed in scanned images shows that for the same inspection position on either peened or unpeened areas, the measured conductivity contribution from inhomogeneity is essentially the same over the whole inspection frequency. Because of the very strict accuracy requirements imposed by the need to measure small (≈0.1–1%) strongly frequency-dependent AECC variations in the presence of much stronger (≈0.5–5%) but also much less frequency-dependent AECC inhomogeneity, every possible measure must be taken to assure that no systematic frequency-dependent error interferes with the data. The four-point absolute calibration procedure used in these measurements effectively eliminates the frequency dependence of the eddy current instrument and the probe coils. However the remnant frequency dependence caused by imperfections of the reference blocks, which are themselves annealed nickel-base superalloys of different composition, cannot be eliminated in this way. In particular, small variations in the relative permeability ($\mu_r \approx 1.0005$–1.005) of these slightly paramagnetic materials could cause an apparent frequency dependence in the measured AECC on the order of a few tenth of a percent. Therefore, in order to eliminate the systematic frequency-dependent error associated with the reference blocks used for calibration purposes, we subtracted from the average AECC spectrum obtained over the peened surface the corresponding average AEEC spectrum measured over the untreated part.

Since the average low-frequency (volumetric) conductivity values calculated over only nine spots on the peened and unpeened parts of the specimen are still inevitably different, often by as much as 1–2%, we normalized each AECC spectra to the

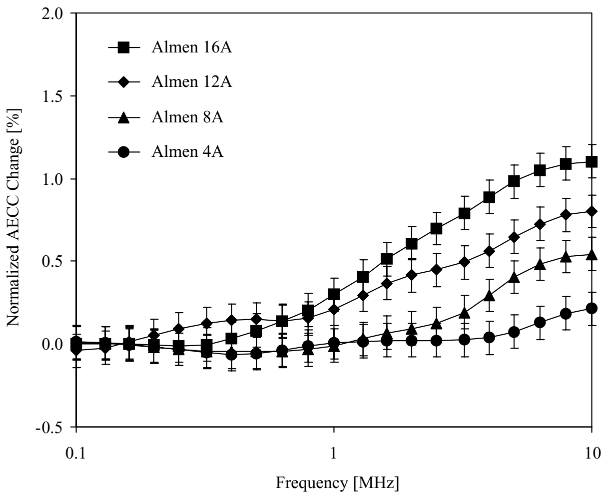

Fig. 8. Excess AECC in shot-peened inhomogeneous Waspaloy at four different peening intensities.

average of the three lowest frequencies (0.1, 0.13, and 0.16 MHz), where the standard penetration depth is approximately 1.5 mm, i.e., sufficiently deep to avoid the surface effects of shot peening, but not too deep to be strongly affected by the volumetric inhomogeneity of the material. This step corresponds to the above described self-referencing baseline subtraction which is necessary to eliminate, or at least significantly reduce, the adverse effects of material inhomogeneity. Figure 8 shows the thereby obtained excess AECC spectra for four different peening intensities in Waspaloy. In intact shot-peened specimens, the excess AECC is roughly proportional to the peening intensity, which is consistent with the results obtained in Ref. 10. Undoubtedly, the experimental uncertainty associated with these AECC spectra is substantially higher than the one previously demonstrated on fully annealed, therefore completely homogenized, Waspaloy specimens.[10] However, considering the level of inhomogeneity present in these specimens, the acceptable agreement obtained with those previously published results well demonstrates the effectiveness of the self-referencing method.

It should be mentioned that for Waspaloy, we would anticipate only a modest 0.5–0.6% change in the electrical conductivity due to stress.[10] However, in the 16A shot-peened Waspaloy sample we actually measured ≈1.1% excess AECC at 10 MHz, which is about twice as high. This overestimation was observed in homogeneous Waspaloy specimens[10] as well as other nickel-base superalloys such as IN100[13] and probably has nothing to do with the inhomogeneity issue at hand. Our preliminary experiments suggest that an unusual phenomenon is responsible for this discrepancy, namely that cold work in excess of 20% plastic strain significantly increases the electrical conductivity in nickel-base superalloys, especially in Waspaloy. This effect of shot peening on the AECC is currently investigated and will be discussed in detail in a follow-up paper.

As noted before, the electrical conductivity inhomogeneity of as-forged Waspaloy does not diminish during thermal relaxation unless the temperature reaches 650–700 °C. An essential feature of the sought NDE capability is that it must be able to detect the drop in residual stress after thermal relaxation from the changing AECC to be useful for life prediction purposes. To determine if the eddy current approach meets this requirement, additional AECC measurements were conducted on as-forged shot-peened samples after full thermal relaxation in order to verify whether the excess AECC measured at high frequencies indeed disappears parallel to the diminishing residual stress. To answer this crucial question, we inspected four as-forged Waspaloy specimens of different peening intensities both before and after full thermal relaxation. Figure 9 shows the excess AECC in shot-peened inhomogeneous Waspaloy at four different peening intensities before relaxation (solid symbols) and after full relaxation for full relaxation for 24 h at 900 °C (empty symbols). Within the uncertainty of the eddy current measurement, the excess AECC completely vanished, which indicates that it is indeed very sensitive to thermal relaxation.

Figure 10a shows the residual stress profiles obtained by X-ray diffraction (XRD) measurements on intact (solid symbols) and fully relaxed (empty symbols) Waspaloy specimens of four different peening intensities. An important byproduct of the XRD stress measurement is the cold work distribution over depth in terms of plastic strain as shown in Figure 10b, which is based on the width of the particular diffraction peak of interest (the 311 peak was used for these measurements). Because the beam width is also affected by microstructural differences between the specimens before and after thermal exposure, the width of the diffraction peak was measured relative to its average value at the three deepest points of the four specimens (i.e., the average of 12 data points), where the surface-treatment induced cold work is known to be negligible. We can

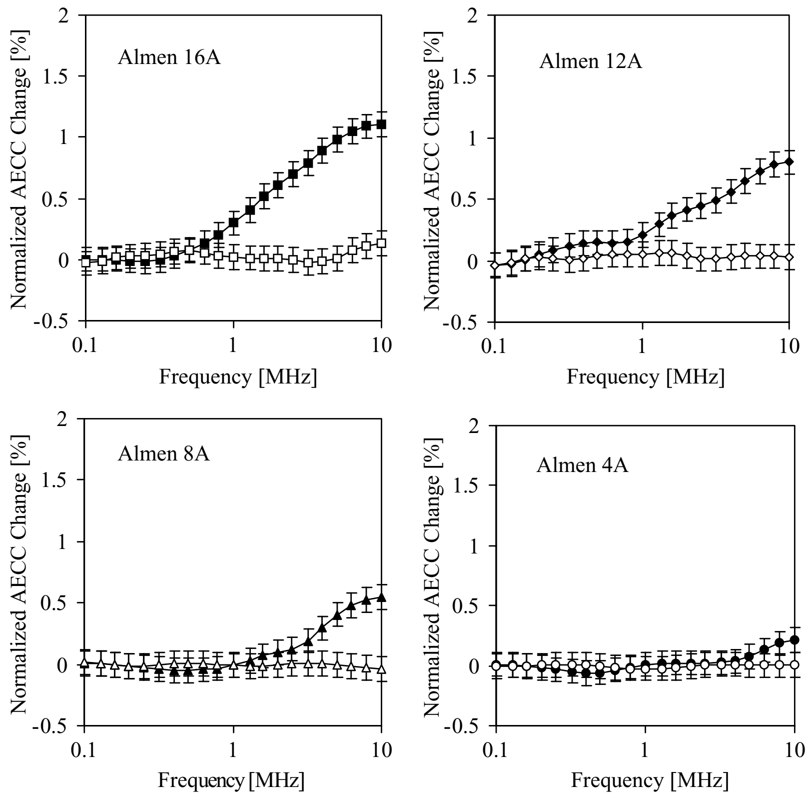

Fig. 9. Excess AECC in shot-peened inhomogeneous Waspaloy at four different peening intensities before relaxation (solid symbols) and after full relaxation (empty symbols).

conclude that the peening intensity has a relatively strong effect on the degree and depth of the resulting cold work in shot-peened samples, with the highest degree of plastic strain occurring just below the surface at each peening intensity. It is evident that essentially complete stress relaxation occurred in the specimens. In comparison, roughly one-fifth of the original cold work effect, which can be fully eliminated only by actual recrystallization, survived below the surface. Since the excess AECC completely vanished in the relaxed specimens after thermal exposure, we can conclude that the eddy current method is not only very sensitive to thermal relaxation, but also that it is mostly sensitive to the residual stress contribution since the cold work effect did not entirely disappear. These results are consistent with our earlier findings in homogeneous Waspaloy,[10] where the peak values of both the AECC increase ($\approx$2%) and the compressive residual stress ($\approx$1700 MPa) were about 70% higher than the corresponding values found in this study for as-received Waspaloy ($\approx$1.2% and $\approx$1000 MPa, respectively). Additional measurements on partially relaxed specimens will be conducted in the future and will be reported along with X-ray diffraction measurements of residual stress and cold work profiles in a followup paper.

4. CONCLUSION

Our experiments indicate that there exist inhomogeneous regions in as-forged Waspaloy specimens, which adversely affect the accuracy of conductivity measurements aimed at near-surface residual stress assessment in surface-treated components. In some cases, a fluctuation on the order of 3-4% was observed in the electrical conductivity not only in as-forged specimens but also after thermal exposure up to about 650 °C. This phenomenon is not associated with the shot peening process and is not a general rule in nickel-base superalloys. For example, according to our experiments, IN718 and IN100, two other nickel-base superalloys commonly used in

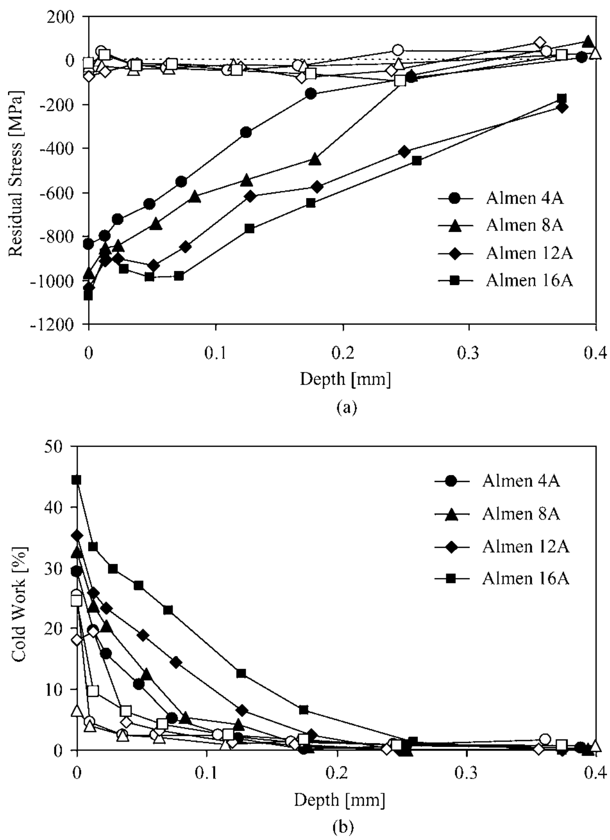

Fig. 10. Residual stress (a) and cold work (b) profiles obtained by X-ray diffraction measurements on intact (solid symbols) and fully relaxed (empty symbols) Waspaloy specimens of four different peening intensities.

turbine engines, do not exhibit such inhomogeneity, though it cannot be excluded that, especially in IN718, a similar inhomogeneity might occur at a lower level in some cases. At this point, the fundamental reason for the difference in electrical inhomogeneity between Waspaloy, IN718, and IN100 is not known.

The main objective of this study was to separate the excess AECC caused by the primary residual stress effect from intrinsic conductivity variations caused by the spurious inhomogeneity exhibited by as-forged nickel-base superalloys. Our experimental results on as-forged Waspaloy specimens indicate that the conductivity variations caused by inhomogeneities in as-forged engine alloys are mostly due to volumetric effects, hence they do not exhibit significant frequency dependence. This independence of frequency can be exploited to distinguish these inhomogeneities from near-surface residual stress and cold work effects caused by surface treatment, which, in contrast, are strongly frequency-dependent. On intact as-forged shot-peened specimens, we have found that the excess AECC was proportional to the peening intensity, while on fully relaxed specimens the excess AECC completely vanished, which indicates that it is fairly selective to the residual stress contribution, since the cold work effect usually does not completely disappear even in fully relaxed specimens.[(10)]

In this paper we investigated the role of electrical inhomogeneity in eddy current residual stress evaluation. It has been shown that this adverse effect can be separated from the primary residual stress effect using a self-referencing method based on the differences in the frequency dependence of the residual stress and inhomogeneity contributions. The increased experimental uncertainty associated with AECC spectra obtained from inhomogeneous specimens relative to the previously studied homogenized Waspaloy specimens necessarily reduces the feasibility of precise residual stress assessment. However, considering the very high degree of inhomogeneity present in some of our specimens, the acceptable agreement obtained with earlier measurements in homogeneous materials is very promising and clearly indicates the feasibility of at least limited eddy current residual stress assessment even in such inhomogeneous materials.

ACKNOWLEDGMENTS

This work was performed at the University of Cincinnati in cooperation with the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory through S&K Technologies, Inc. on delivery order number 5007-IOWA-001 of the prime contract F09650-00-D-0018. Additional support was provided by the Department of Air Force under Contract No. #F33615-03-D-5204 (NTIP II) Subcontract #04-S508-010-04-C1. The authors wish to thank Quintin Ullery, Ashley Keeling, and Hassan Al-Atat at the University of Cincinnati for their contributions to some of the eddy current measurements reported in this paper and Professor Rosario Gerhardt of Georgia Tech for valuable discussions concerning microstructural variations in nickel-base superalloys. The specimens used in this study were machined at Metcut Research, Inc., the shot peening was performed by Metal Improvement Co., and the X-ray diffraction measurements were done by Lambda Research.

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